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USAFGL ltr, 1 Aug 1983

AFCRL-TR-75-0097
AIR FORCE SURVEYS IN GEOPHYSICS, NO. 300

AD B004427

Final Report of PVM-4 and PVM-3 Weather Documentation

AFCRL/Minuteman Report No 2

JAMES I. METCALF, Capt, USAF
ARNOLD A. BARNES, Jr.
MICHAEL J. KRAUS

19 February 1975

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFCRL-TR-75-0097	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): FINAL REPORT OF PVM-4 AND PVM-3 WEATHER DOCUMENTATION AFCRL/MINUTEMAN REPORT NO. 2	5. TYPE OF REPORT & PERIOD COVERED: Scientific. Final
	6. PERFORMING ORG. REPORT NUMBER: AFSG No. 300
7. AUTHOR(s): Capt James I. Metcalf, Arnold A. Barnes, Jr., Michael J. Kraus	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Air Force Cambridge Research Laboratories (LY) Hanscom AFB Massachusetts 01731	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 133B0001
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Cambridge Research Laboratories (LY) Hanscom AFB Massachusetts 01731	12. REPORT DATE: 19 February 1975
	13. NUMBER OF PAGES: 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; (Test & Evaluation/ Operational Testing of Equipment/Systems); (19 February 1975). Other requests for this document must be referred to AFCRL (LY), Hanscom AFB, Massachusetts 01731

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Minuteman
Aircraft weather measurement
Radar weather measurement
Tropical cirrus cloud
Water content profiles

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Re-entry weather encountered by Minuteman tests PVM-4 and PVM-3 is described in this report. Documentation was accomplished by WC-135B and WB-57F aircraft, by radar, and by lidar. Weather was essentially clear for each mission except for high thin cirrus layer clouds (water content less than 0.003 gm m^{-3}) encountered by PVM-4. Low level clouds were present on each day. Data from all sources are presented, and operational problems of the weather documentation plan are discussed.

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Preface

AFCRL participation in the Minuteman Natural Hazards Program was first formulated in the spring of 1973. At that time, the SAMSO Deupty for Minuteman requested the support of AFCRL in developing a weather data acquisition plan and in performing post-flight analysis of the weather data. Prior to the receipt of this request the Minuteman PVM-4 test had been conducted, with radar weather data along the re-entry trajectory supplementing the normal re-entry area weather observations. By the time of the PVM-3 test a more complete data acquisition plan had been developed and the full-fledged Weather Team had been deployed to Kwajalein Missile Range. The field support included representatives of SAMSO/MN; SAMTEC/WE; 9th Weather Reconnaissance Wing (58th Weather Reconnaissance Squadron); 6th Weather Wing; AFCRL Meteorology Laboratory; TRW Systems Group; Meteorology Research, Inc.; Edgerton, Germeshausen, and Grier, Inc.; Particle Measuring Systems, Inc.; and Stanford Research Institute. TRW was responsible for overall planning and operation of the test.[1] The roles of the other organizations are described in this report. MRI and SRI in particular were responsible for the operation of the aircraft instrumentation and the lidar, respectively. Readers interested in more details of their equipment or data than are presented here, are referred to their final reports for these missions.[2,3]

1. Wilmot, R.A., Cisneros, C.E., and Guiberson, F.L. (1974) High cloud measurements applicable to ballistic missile systems testing. 6th Conf. Aerosp. and Aeronaut. Meteor., Amer. Meteor. Soc., pp 194-199.

2. Jahnsen, L.J., and Heymsfield, A.J. (1974) Final report of PVM-3 Mission WB-57F Instrumentation and Cloud Particle Measurements. MRI 74 FR-1155, Meteorology Research, Inc., Altadena, Calif.

3. Uthe, E.E. (1973) Light Detection and Ranging (LIDAR) Support for PVM-4 and PVM-3 Re-entry Operations. SRI project 2565-5, Stanford Research Institute, Menlo Park, Calif.

Preface

This report is the second in the AFCRL Minuteman series. The first report described the analysis of the aircraft and radar weather data for the PVM-5 test in April 1974.

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1. INTRODUCTION

Comprehensive weather data acquisition in support of Minuteman tests began with PVM-4 and PVM-3, which were launched on 1 June and 24 August 1973, respectively. Because of the similarity of the weather objectives for these tests, and because the weather support plans were still being formulated at the time of PVM-4, it was decided to combine the analytical results from these tests into a single report. In discussing each of these tests we intend to present our best estimate of the water content through which the re-entry vehicles passed and to present data from various meteorological sensors which provide further detail on the local weather, both on the macroscale of clouds and weather systems and on the microscale of particle shapes and sizes.

Details of each of the sensors are included with the presentations of data in the following sections. The locations of the various supporting facilities are shown in Figure 1. The NWS radiosonde and weather radar facilities and the DMSP (formerly DAPP) satellite van operated by 6th Weather Wing from McClellan AFB were located on Kwajalein Island. The lidar operated by SRI was located on Gellinam Island, close to the re-entry corridor. The Lincoln Laboratory radars, located at KREMS on Roi-Namur Island, were used to obtain weather data on the re-entry trajectories. Two WB-57F aircraft operated by the 58th Weather

(Received for publication 14 February 1975

Reconnaissance Squadron from Kirtland AFB were based at Kwajalein for the PVM-3 test support. An Air Weather Service WC-135B aircraft was based at Guam and flew to the Kwajalein area for support of each of these missions.

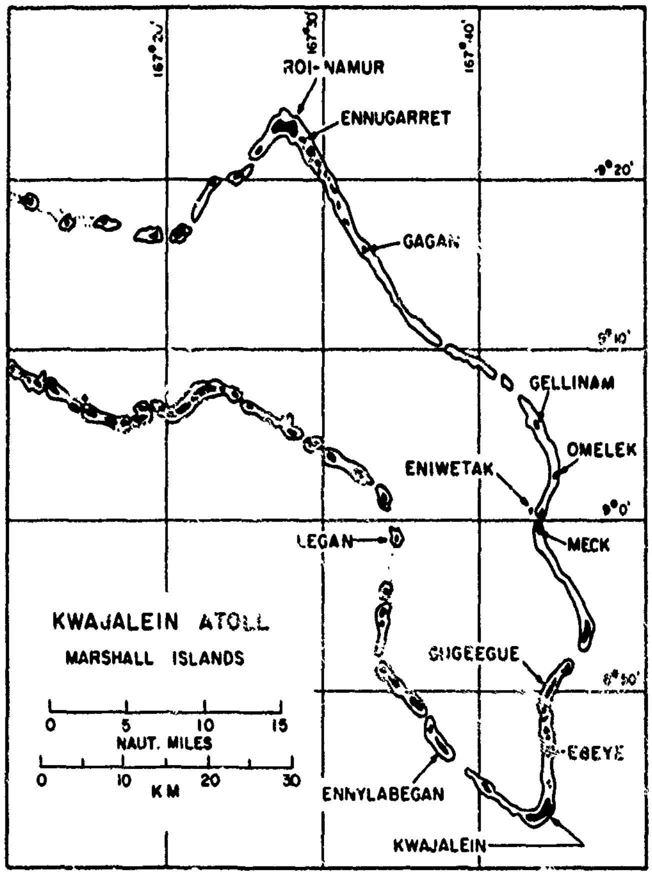

Figure 1. Kwajalein Atoll, Showing the Islands Occupied by the Facilities of Kwajalein Missile Range. Range Operations Control Center, aircraft support facilities, NWS radars, and MPS-36 radars are at Kwajalein Island, Lincoln Laboratory radars are at Roi-Namur Island

Analysis shows that the weather objectives for each of these missions were met. Several thin and weak radar echo layers with water content 0.001 gm m^{-3} or less were detected below 6 km on one of the PVM-4 trajectories, and the lidar detected a thin cirrus layer at 15 km. Radar trajectory scans following PVM-3

showed no clouds above 1.8 km on any of the trajectories. Lidar observed thin layers intermittently at about 12 and 16 km during several hours before and after PVM-3 re-entry but none at the time of re-entry.

2. PVM-4 RE-ENTRY WEATHER

The PVM-4 test was conducted on 1 June 1973, with impact at approximately 0340Z. The DMSP satellite pass at 0138Z (Figure 2) showed a large mass of

Figure 2. DMSP(DAPP) Satellite Visual Data for 1 June 1973, 0138Z. Cumulonimbi about 550 km west and 100 km east of Roi-Namur are principal source regions of high-altitude cirrus. These are moving westward with the low-level winds and will be out of the re-entry area by the time of re-entry

cumulonimbus and cirrus cloud about 550 km W of Roi-Namur, with cirrus blowing eastward at about 12° N. The tops near the source were determined from the infrared data to be above 15 km. A somewhat smaller cloud mass was located about 100 km E of Roi-Namur. Infrared data also indicated the presence of very thin cirrus over the lagoon and for about 30 km E of Gagan, and broken cirrus just N and E of Roi-Namur. Broken clouds in these areas were low- and middle-level clouds which were also reported by the WC-135B weather reconnaissance aircraft.

Observations by the WSR-57 radar also showed the area of clouds extending east and west across the northern half of the atoll at 0025Z, gradually moving westward with the low-level winds. Maximum cell tops were reported at 7.6 km in the early observations, dropping to near 5 km at 0230Z. At 0300Z a small group of weather echoes was detected about 100 to 175 km NE of Kwajalein, with maximum cell tops about 6 km. The 0351Z observation (Figure 3) showed the closest edge of these echoes at about 70 km range.

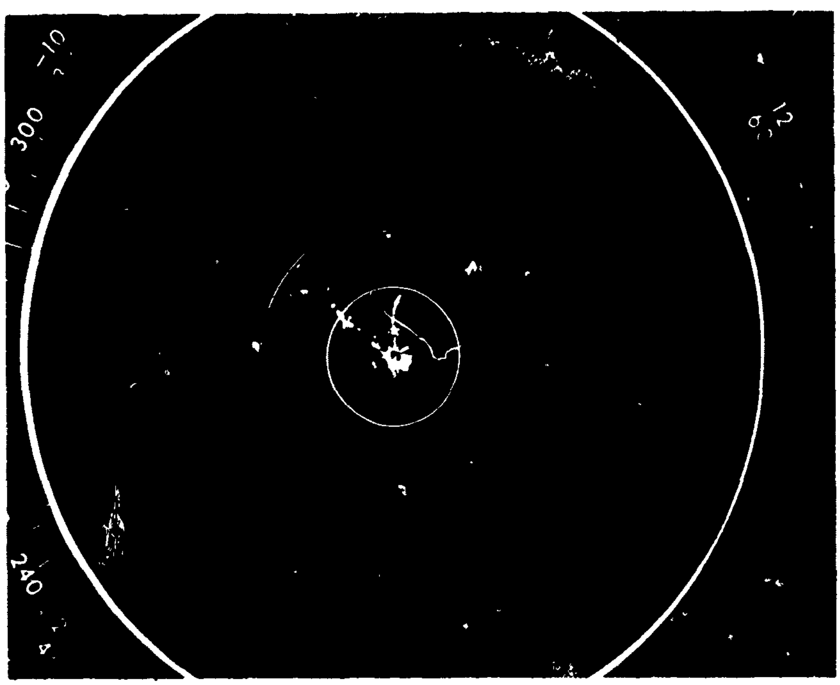

Figure 3. WSR-57 PPI at 0351Z, 1 June 1973. Elevation angle is 0° and range markers are at 10 nm (18.5 km) intervals out to 50 nm (92.6 km). Ground echoes from the atoll islands appear to the north and northwest as far as 35 km. Weak echoes from a group of convective cells are barely discernable at 70 to 90 km range and 45-62° azimuth

Soundings from Kwajalein at 0336Z and from Roi-Namur at 0340Z are shown in Figure 4. The winds were easterly at 10 to 13 m sec^{-1} up to 5 km, then veered to southerly about 6 km and westerly at 10 to 20 m sec^{-1} between 9 and 16 km. Above the tropopause (17 km) the winds were again easterly. The moisture was high (>60%) up to 5 km; maxima occurred at 0.3 to 0.6 km and 4.3 to 4.9 km. A layer with RH ≅ 70% was observed at 7.0 to 7.6 km.

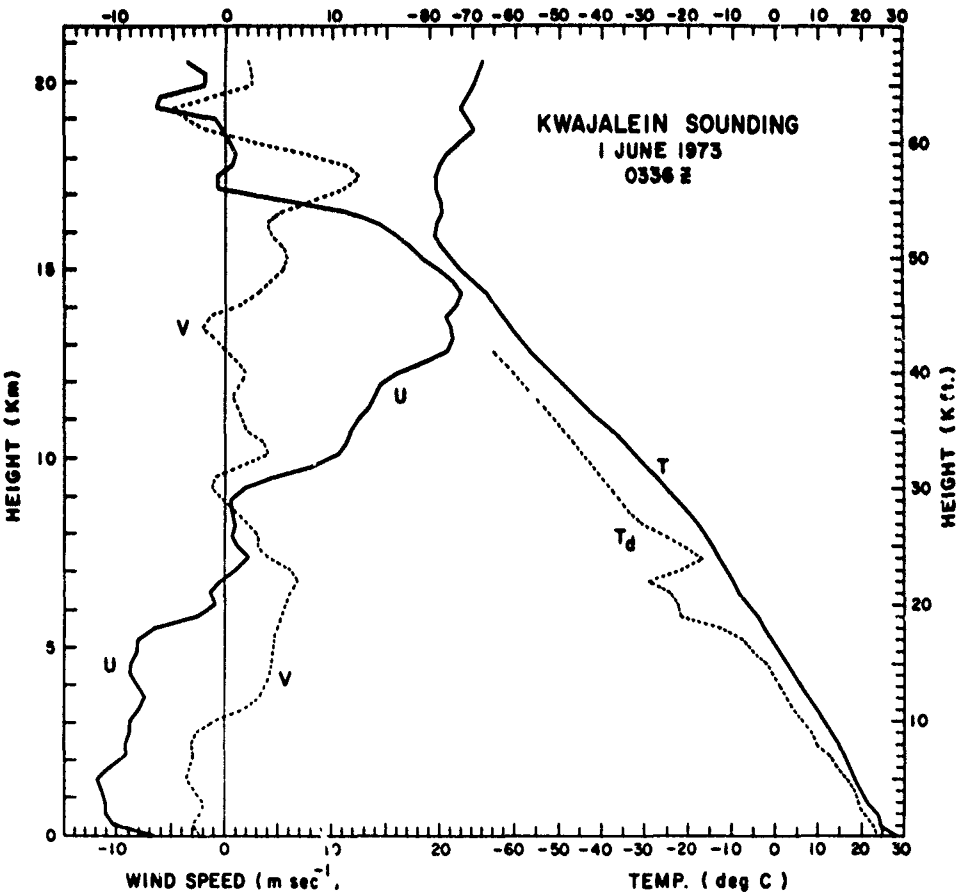

Figure 4a. Sounding at 0336Z From Kwajalein, 1 June 1973. Wind components are toward the east (U) and toward the north (V). Winds are easterly below 5 km and westerly between 9 and 16 km. The freezing level is at 5 km and the tropopause at 17 km. Above the tropopause winds are easterly again. Highest humidity is below 5 km associated with low-level convective mixing; a layer of high humidity is also observed at 7.0 to 7.6 km

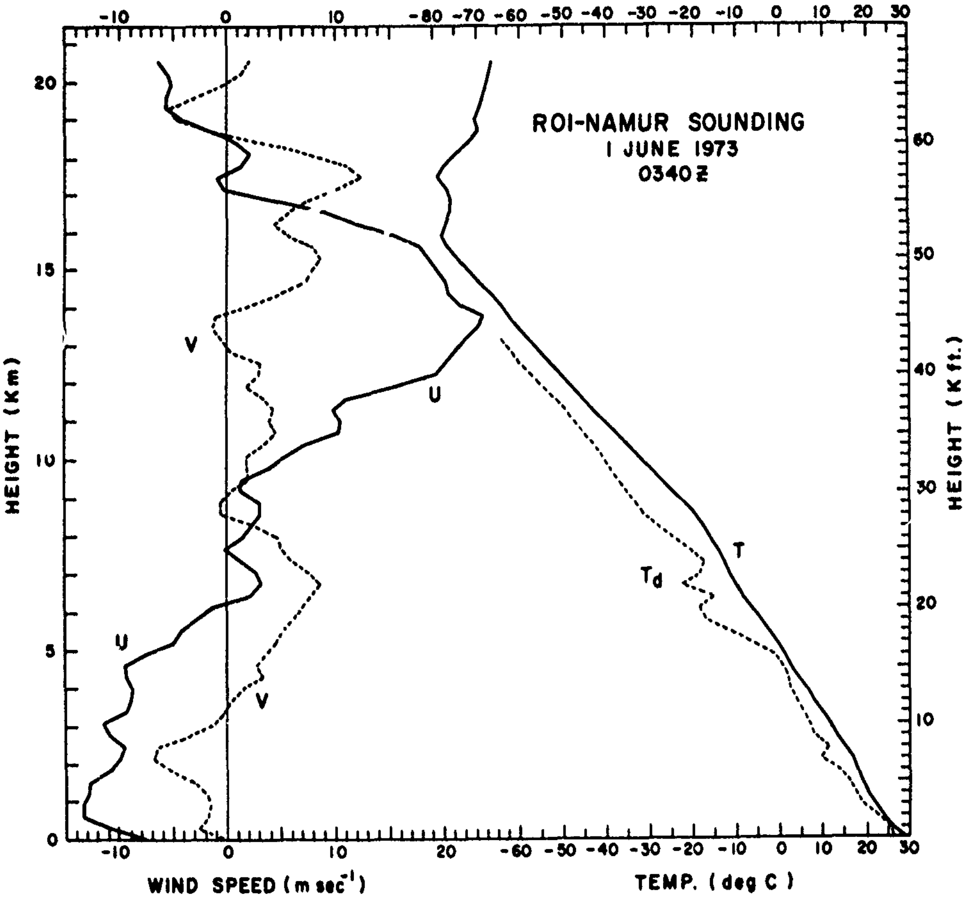

Figure 4b. Sounding at 0340Z From Roi-Namur, 1 June 1973. See legend of Figure 4a

The SRI Mark IX lidar[3] was at KMR from 23 May to 2 June 1973. The Mark IX system uses a pulsed ruby laser at a wavelength of 6943 Å. Backscattered signal intensity, which depends primarily on the integrated cross-sectional area of the cloud or aerosol particles, was measured and provided a means of determining ice water content or density. (Signal attenuation may limit the accuracy of the lidar measurements in thick clouds.) A summary of the lidar operations is presented in Table 1. On PVM-4 mission day the lidar operated from 0242Z to 0500Z with a maximum range of about 23 km for vertical scans and 20 km for angular scans. Angular scans at 60° azimuth and scans of the re-entry trajectory were made at 0323 and 0355Z. A low-density cirrus layer about 300 m thick was observed near 15 km from about 0242Z on the vertical scans through 0355Z on the

angular scans. This layer could not be detected on the trajectory scans due to the greater range. Maximum ice water content for this layer was estimated as 4.3×10^{-4} gm m^{-3}. The SRI report concludes "that PVM-4 penetrated the near 15 km low-density cirrus layer, but most likely did not penetrate lower convective clouds that were in the area."

Table 1. Lidar Data Summary, May to June 1973

Date	Time (GMT)	Number of shots	Rate (pulses/ min)	Remarks
24 May	≈ 0400 to ≈ 0405	100	20	Lidar check, Kwajalein
25 May	2245 to 2325	800	20	Gellinam Island sensor correlation tests (2315 and 0300Z)
26 May	0245 to 0313	480	20	
29 May	2118 to 2229	1,280	20	
	2229 to 2329	640	10	Sensor correlation tests (2315Z)
30 May	0238 to 0246	160	10	Sensor correlation tests (0300Z)
	0255 to 0344	160	10	
31 May	0207 to 0322	1,440	20	PVM-4 recycle 24 hours
	0338 to 0355	320	20	
31 May	2330 to 2338	160	20	
1 June	0040 to 0056	140	20	
	0147 to 0219	640	20	PVM-4 Operations:
	0242 to 0322	800	20	Vertical time scans
	0323 to 0339	160	20	Angular scans
	0340 to 0344		60	Individual shots
	0345 to 0355	160	20	Angular scans
	0355 to 0427	640	20	Vertical time scans
	0427 to 0500	1,280	20	Sensor correlation tests (0450Z)
	0820 to 0925	640	20	
2 June	0543 to 0557	160	20	TPQ-11 tests, Kwajalein
2 June	2022 to 0036 (3 June)	4,800	20	TPQ-11 tests, Kwajalein
3 June	0041 to 0108	480	20	

Visual observations from the WC-135B indicated some cirrus near 10.1 km at 0145Z, and a thin cirrus layer above. Later observations at 0250Z, and 11.3 km altitude showed multi-layered cirrus just above the aircraft and a thin layer much higher. The cirrus was still visible in the re-entry corridor close to launch time. NWS surface observations at 0341Z were scattered clouds at 0.4 km (2/10 cumulus) and 4.3 km (1/10 altocumulus) and thin overcast at 9 km (9/10 cirro-stratus).

ALCOR weather scans were made on one trajectory following RV impact. Six scans were made from 20 km to the surface beginning at 0341Z. Data were provided to AFCRL as calibrated radar cross-section values in 170 range gates spaced across a 2.5 km interval approximately centered at the radar tracking point. We processed these to yield range-height arrays of weather reflectivity factor Z ($mm^6\ m^{-3}$) by the equation

$$Z = C\sigma/r^2 \tag{1}$$

or

$$dBZ = 10 \log C + 10 \log \sigma - 20 \log r$$

where σ is the cross section (m^2), r is the range (km) and

$$C = \left[\frac{\lambda^4 \times 10^{10}}{\pi^5 \times |K|^2}\right] \left[\frac{8 \ln 2}{\pi \theta^2 h \times 10^6}\right] \tag{2}$$

where λ is the wavelength (5.30 cm), h the pulse length (37.5 m), θ the beam width (5.24×10^{-3} rad), and $|K|^2 = 0.197$ for radar backscatter from ice crystals. Thus $10 \log C = 83.5$ for ALCOR. The quantity Z is the factor of the received signal power which is dependent only on meteorological parameters. It is equal to the sixth moment of the particle size spectrum, and thus is not a direct measure of the water content which is proportional to the third moment of the spectrum, that is, the volume.

Because ALCOR transmits a frequency-modulated "chirp" pulse, the pulse length used in the above computation is not a physical pulse length, but rather a compressed pulse length corresponding to the output of a pulse-compression network in the radar receiver. At the time these computations were first made we had not determined the absolute accuracy of the Z values. Subsequently we conducted comparisons of chirp and constant-frequency radar weather data with the TTR-4 radar at Kwajalein[4] and determined that the reflectivities originally computed by Eqs. (1) and (2) from the chirp data were 3 dB low.

4. Metcalf, J.I., Barnes, A.A., Jr., and Nelson, L.D. (1975) Water content and reflectivity measurement by "chirp" radar. 16th Radar Meteor. Conf. Amer. Meteor. Soc., pp 492-495.

The radar data shown in Figure 5 are from the first two of the postmission trajectory scans. Because the freezing level was near 5 km we computed the reflectivities using $|K|^2 = 0.93$, appropriate to raindrops, in Eq. (2). We also added 3 dB to compensate for the error of the earlier computations, so that $10 \log C = 79.8$. The trajectory scans show no echoes above the noise level at any altitude above 5 km. Several echo layers appear below 5 km, as marked in the

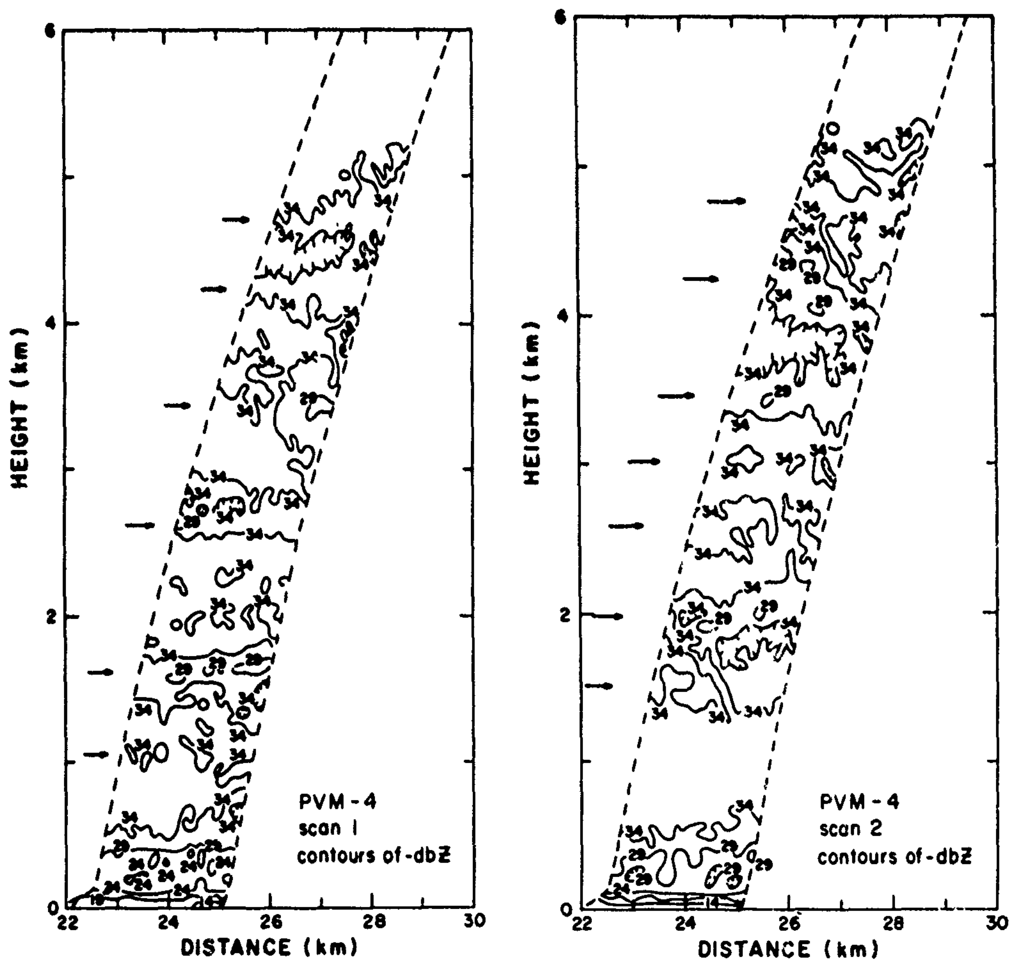

Figure 5. ALCOR Scans of PVM-4 Trajectory at 0341Z and 0346Z, 1 June 1973. Contours are of -10 log Z, with Z in $mm^6\ m^{-3}$. Echoes below 5 km are due to low-level convective activity. No echoes are observed above 5 km, indicating no clouds denser than 0.003 gm m^{-3}

figures, but none stronger than -24 dBZ (4.0×10^{-3} mm^6 m^{-3}), except in the ground echoes below 400 m. Because the observed echoes were below the freezing level, we determined water content by a Z-M equation appropriate to tropical rain, namely,

$$M = 0.011\, Z^{0.43} \tag{3}$$

derived from equations presented by Battan.[5] (It should be noted that this Z-M equation was derived from surface observations and is therefore not strictly applicable to observations in clouds; however, it is useful for order-of-magnitude estimates of the cloud water content.) Thus the layers have maximum water contents about 0.001 gm m^{-3}. Above 5 km the minimum detectable reflectivity is approximately -27 dBZ, increasing to about -22 dBZ at 20 km on the trajectory. The approximate ice water content represented by these signal levels may be determined from the relation

$$M = 0.038 Z^{0.529} \tag{4}$$

which is applicable to bullet and column ice crystals.[6] Thus, -22 dBZ represents 2.6×10^{-3} gm m^{-3}, and the upper limit of undetectable water content does not contradict the value computed from the SRI lidar data for the cirrus layer at 15 km.

Re-entry weather for PVM was essentially clear. Several weather echoes were detected by radar below 6 km on the trajectory. Visual observations from the surface and from the WC-135B aircraft indicated several thin layers of cirrus above 10 km, one of which was detected by lidar at 15 km. The water content of each of these clouds was less than 0.003 gm m^{-3}.

The weather severity index used as a launch criterion for later tests in this series is defined by

$$WSI = \int_{h_1}^{h_2} M\, h\, dh \tag{5}$$

where h_1 is normally equal to zero, and h_2 is the height (km) of the highest cloud top on the trajectory. (The units of WSI are gm km^2 m^{-3}, but it is commonly used without units.) In the present case where the weather consists mainly of a few thin layers, this may be approximated by a summation over all the cloud layers:

5. Battan, L.J. (1973) Radar Observation of the Atmosphere. Univ. of Chicago Press, 324 pp.

6. Heymsfield, A.J. (1973) The Cirrus Uncinus Generating Cell and the Evolution of Cirriform Clouds, PhD Thesis, The University of Chicago.

$$\mathrm{WSI} \cong \sum_i M_i \bar{h}_i \Delta h_i \tag{6}$$

Radar alone cannot measure WSI less than about 0.5, as this value corresponds to the minimum radar-detectable water content (about 0.0025 gm m^{-3} on the PVM-4 trajectory) in Eq. (5) integrated from 0 to 20 km. Observations by lidar and by eye can reduce this lower limit considerably. The PVM-4 WSI based on cloud layers actually observed was less than 0.01.

3. PVM-3 WEATHER DESCRIPTION

The PVM-3 test was conducted on 24 August 1973 with impact at 0203Z. Heavy clouds associated with the inter-tropical convergence zone that had been over Kwajalein, dissipated about a day before the PVM-3 launch. A persistent cirrus overcast broke up about 12 hr before launch time.

DMSP satellite pictures taken at 0137Z (Figure 6) showed the target area to be clear in both visual and infrared bands. Photos on both bands showed indications of cumulus clouds just north of Kwajalein Island. The infrared photo also showed signs of thin cirrus immediately south of Roi-Namur.

The WB-57F aircraft made a photo run at 18 km (60 kft) over the re-entry corridor about 25 min before impact. Photographs from the downward-looking panoramic camera (Figure 7) showed low-level fair-weather cumulus with less than one tenth coverage in the area of interest. Layers of clouds at many different levels were seen toward the horizons north and south of the corridor, but not in the corridor. Some thin virga were visible to the east of the atoll and slightly north of the northernmost RV trajectory.

The WB-57F forward-looking camera film showed some thin layers of haze or tenuous clouds in the corridor 2 hr after impact. Both the WB-57F and the WC-135B reported visible cloud layers above 7 km in the corridor 1 to 4 hr before impact. However, these visual observations do not seem to be representative of the cloud conditions as detected by the other sensors at the time of impact.

The NWS 10-cm WSR-57 weather radar at Kwajalein can detect precipitation but cannot detect non-precipitating clouds. This radar showed no precipitation areas in the re-entry corridor at impact time (Figure 8). The 0.86-cm TPQ-11 vertically-pointing radar can detect non-precipitating clouds but is subject to strong attenuation in precipitation. The TPQ-11 showed fair-weather cumulus with bases about 500 m (1600 ft) and tops mostly near 1200 m (4000 ft) but occasionally up to 2 km.

The Kwajalein rawinsonde at 0205Z (Figure 9) revealed high humidity (RH>60%) up to 7 km. At this level the dew point temperature dropped off sharply and the wind shifted from easterly to southerly. This layer appeared as a very thin layer on the ALCOR vertical scans. The ALCOR echoes are attributed to a

large gradient of the refractive index, not to clouds. The rawinsonde also showed moist layers at 9 and 11 km, corresponding to cloud layers observed by the WB-57F.

Lidar operations from 18 August to 24 August 1973 are summarized in Table 2. On PVM-3 mission day the lidar, at Gellinam Island, operated continuously from 1915Z (23 August) to 0443Z (24 August), generally in a fixed vertically-pointing mode. From 0151Z to 0209Z elevation scans were taken in the re-entry corridor. SRI reported, "Data collected while the lidar was scanning in the direction of the re-entry corridor indicated that no clouds existed above 10 kft during PVM-3 re-entry".[3]

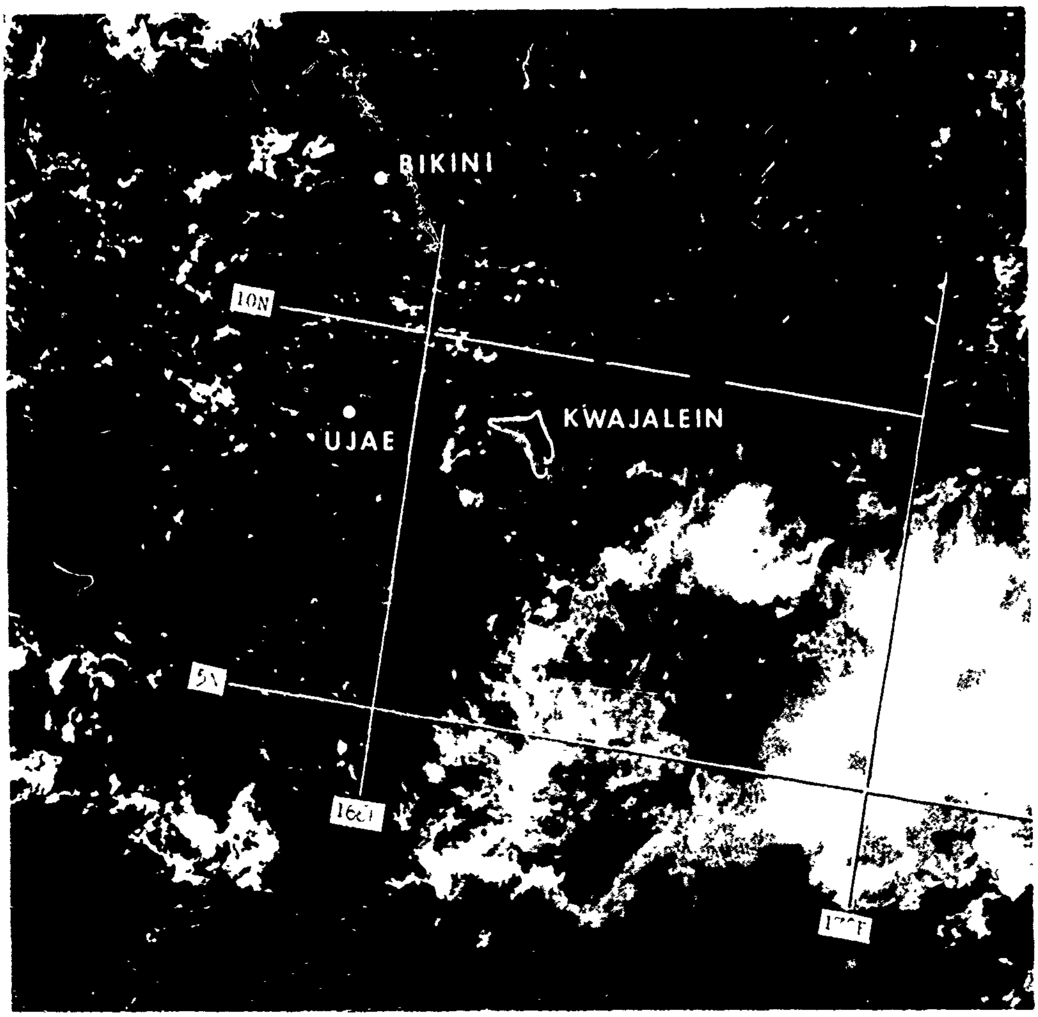

Figure 6. DMSP(DAPP) Satellite Visual Data for 24 August 1973, 0137Z. Thick clouds can be seen about 200 to 300 km ESE and S of Kwajalein. There are no major developments in the vicinity of Kwajalein

Figure 7. Montage of Photographs From WB-57F Downward-looking Camera. Flight is at 18 km altitude at a true heading of 236° along the re-entry corridor at 0136 to 0140Z. High clouds can be seen toward the horizons, both north (right) and south. Re-entry corridor is clear except for low-level cumulus. Eastern side of Kwajalein atoll appears in the upper part of the figure

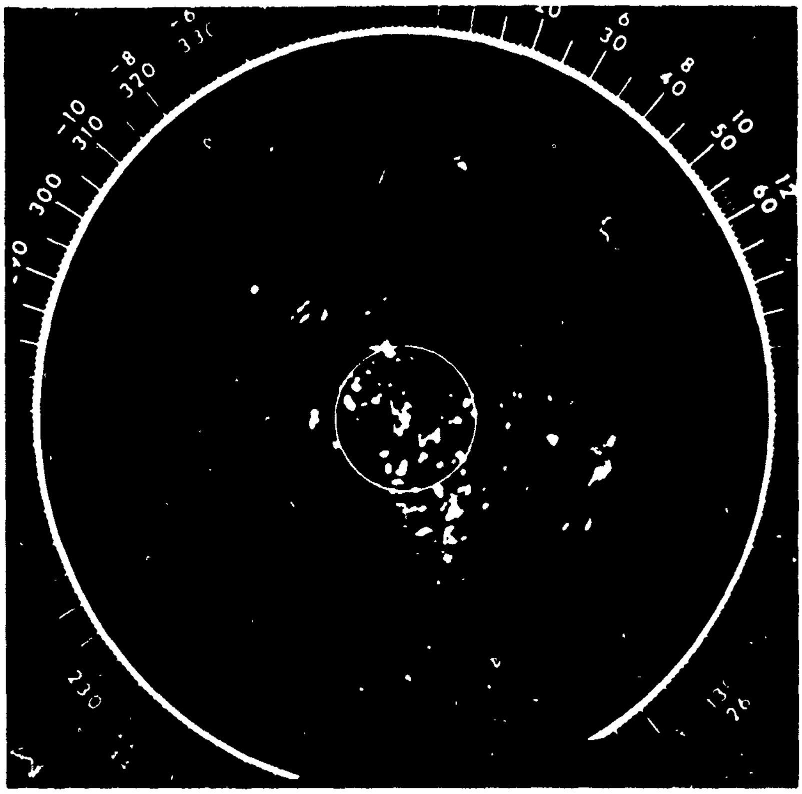

Figure 8. WSR-57 PPI at 0220Z, 24 August 1973. Elevation angle is 0° and primary range markers are at 50 nm (92.6 km) intervals out to 250 nm (463.0 km). Ground echoes from the atoll islands appear to the north and northwest as far as 35 km. Numerous echoes from showers are present, particularly in the southeast and northwest quadrants. A large shower is located about 85 to 100 km at 345° azimuth, just north-northwest of Roi-Namur. No significant echoes are present in the re-entry corridor

The RADOT's observed two of the three RV's in clear air all the way to the surface. The third RV was reported to have been in the clear all the way, but parts of the trajectory apparently were not recorded by the RADOT's. One of the ballistic cameras was thought to have followed this RV to the surface, but this report has not been confirmed.

Quantitative measurements of the re-entry area weather by aircraft and radar are described in the following sections. Evaluation of these data, for determining the satisfaction of the launch criteria and for directing the aircraft in its post-mission sampling operations, was accomplished by the mission Weather Team. The Weather Team consisted of representatives of AFCRL, SAMSO, SAMTEC, TRW, and MRI at the ROCC and an AFCRL radar meteorologist at KREMS.

Table 2. Lidar Data Summary, August 1973

Date	Time (GMT)	Number of Shots	Rate (pulses/ min)	Remarks
18 Aug	2107 to 0530 (19 Aug)	2,240	5	TPQ-11 tests, Kwajalein, 10 dB in video
20 Aug	0332 to 0400	160	5	Lidar checkout at Gellinam Island
20 Aug	2130 to 2138	160	20	0 dB in the receiver and video for rest of experiment
	2154 to 0040 (21 Aug)	960	5	45° observations (100 shots) to reduce background
21 Aug	0040 to 0310	640	5	Lidar turned off during WB-57F overpass
21 Aug	2354 to 0131 (22 Aug)	480	5	Heavy overcast
22 Aug	0216 to 0249	160	5	PVM-3 recycled 24 hours
22 Aug	1922 to 1955	160	5	PVM-3 recycled 24 hours
	1955 to 0030 (23 Aug)	706	2	Range control requested Lidar turned off
23 Aug	19[illegible] to 0147 (24 Aug)	1,958	5	PVM-3 launch day angular scans (35° to 90° El; 55° Az)
24 Aug	0151 to 0209	825	60	
	0210 to 0235	480	20	WB-57F overflights
	0235 to 0443	≈1,250	10	
25 Aug	1101 to 1117	160	10	TPQ-11 tests at Kwajalein, no structure observed
	1118 to 2025	2,720	5	TPQ-11 tests, no high clouds observed

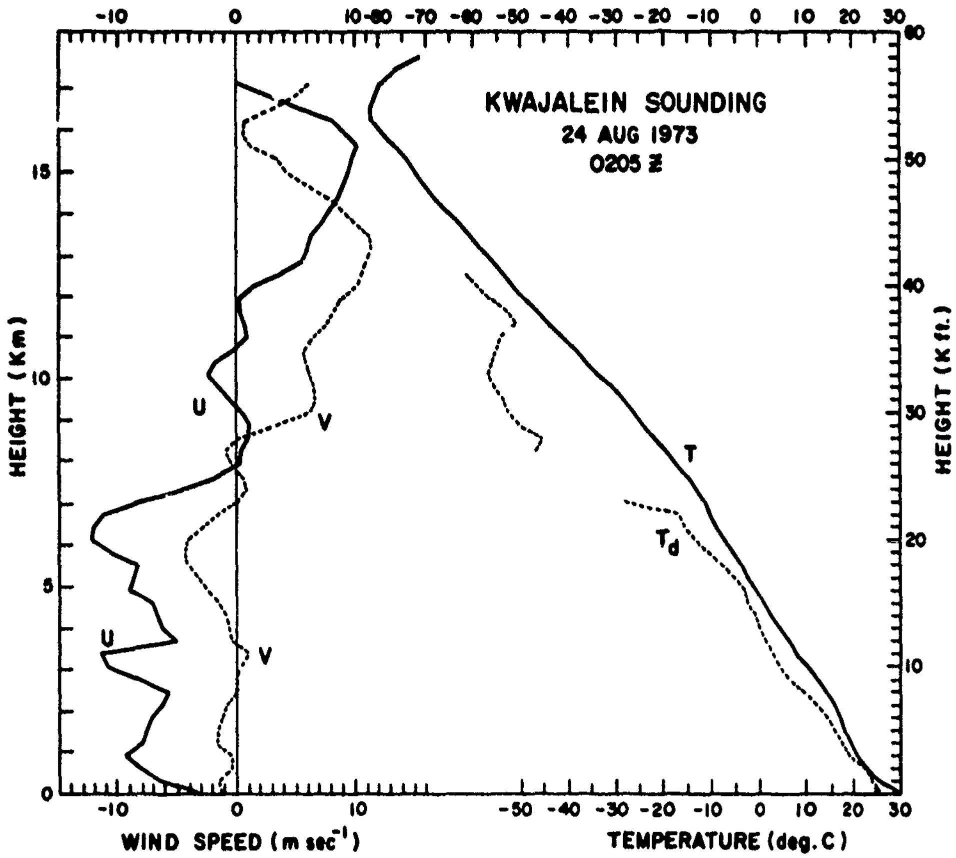

Figure 9. Sounding From Kwajalein at 0205Z, 24 August 1973. Wind components are toward the east (U) and toward the north (V). Winds are easterly below 7 km, southerly from 9 to 12 km, and gradually veering to westerly at 16 km, just below the tropopause. Significant humidity (>60%) is observed only below 7 km

4. PVM-3 AIRCRAFT DATA

Two WB-57F aircraft were at Kwajalein during the period 12 to 24 August 1973. The operations during that time are shown in Table 3. Flights prior to launch day were performed for purposes of instrumentation checkout and vectoring practice. Details of objectives and accomplishments of these flights have been provided by MRI.[2]

Table 3. WB-57F Operations at Kwajalein, August 1973

Date (Aug 73)	Time (GMT)	Pressure Altitude (kft)	Flight Mode
15	0330	45	Ascent in corridor and photo-mapping run
		45 40 20	Cloud sampling with MPS-36
16	0250	60	Ascent in corridor and photo-mapping run
		54 40 30	Cloud sampling with MPS-36
20	0455	5 20 45	Cloud sampling
21	0105	60	Ascent in corridor and photo-mapping run
		53.5 44 39	Cloud sampling with MPS-36, ALCOR, and lidar
23	0200	45 41 37 34 27	Cloud sampling with MPS-36 and ALCOR
24	0105	60	Ascent in corridor and photo-mapping run
	0212		Descent to 25 kft and ascent
	0316 0330 0344 0358 0415 0426	56 (17.1 km) 54 (16.5 km) 44 (13.4 km) 40 (12.2 km) 36 (11.0 km) 28 (8.5 km)	Cloud sampling with MPS-36, ALCOR, and lidar

Cloud physics instrumentation was housed in two removable pods mounted near the outer end of each wing, as shown in Figures 10 and 11. These are described in detail by Jahnsen and Heymsfield.[2] The principal instruments were the PMS probes, which measured particle sizes in the ranges 1 to 31 μ (axially scattering spectrometer), 7 to 210 μ (optical array cloud droplet spectrometer), and 164 to 2170 μ (optical array precipitation spectrometer). A Formvar particle replicator (MRI Model 1203) provided a continuous record of the types of hydrometeors encountered by the aircraft. Images of particles greater than 2 μ in length were preserved in an adhesive resin applied to a 16-mm sampling tape. These data are essential to the analysis of the PMS data, as the computation of ice water content

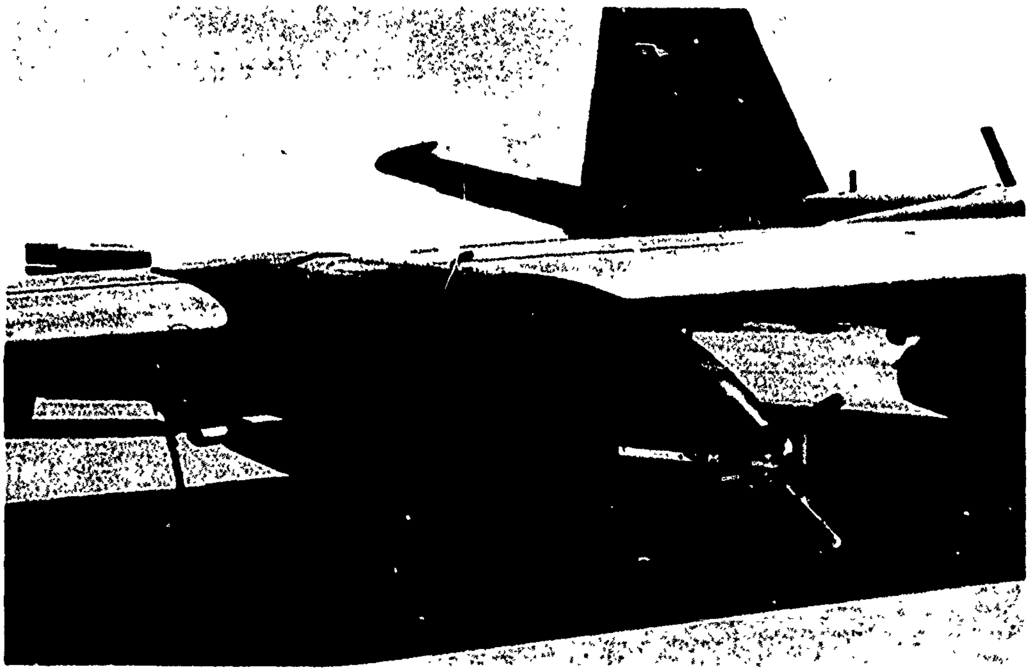

Figure 10. Instrumentation Pod on Right Wing on WB-57F Aircraft. Precipitation spectrometer is at the forward end of the pod, and MRI replicator is on the side

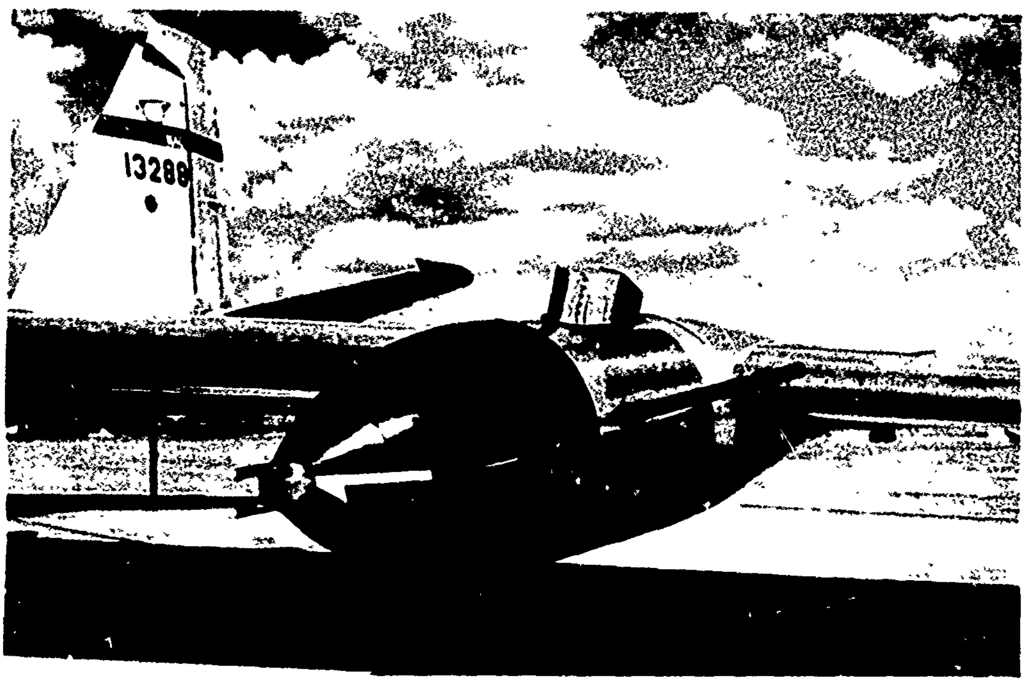

Figure 11. Instrumentation Pod on Left Wing of WB-57F Aircraft. Cloud droplet spectrometer is at the forward end, axially scattering spectrometer is on the side, and MRI foil sampler is on the top

and reflectivity from the one-dimensional size spectra requires an approximation of the crystal habit. A second hydrometeor sampler (MRI Model 1220 foil impactor) recorded images of particles greater than 250 μ in size on a thin metallic film. Additional instrumentation measured temperature, pressure altitude, and indicated airspeed, which were recorded along with observations by the crew. MRI was responsible for the aircraft instrumentation in general, and EG& G operated the on-board tape recorders.

The WB-57F's were equipped with forward- and downward-looking cameras which were used to supplement the other sensors. The downward-looking F415P camera was used only during the pre-impact high altitude photo-mapping run, as described in Section 3.

The aircraft flight patterns are shown in Figure 12. A spiral ascent was made in the re-entry corridor about 0115 to 0126Z, to obtain a qualitative profile of clouds. The crew reported very thin wispy cirrus near 17 kft (5.2 km) and between 29 and 3[illegible] (8.8 to 10.1 km). While in the holding area west of the atoll about the time [illegible] re-entry, the aircraft descended to 25 kft (7.6 km). The aircraft penetrated thick virga (cirrus uncinus) about 9.7 to 11.9 km, with maximum ice water content 0.123 gm m^{-3} in the upper part and 0.055 gm m^{-3} in the lower part. The crew pointed out that this cirrus was only in the holding area, not in the re-entry corridor.

MINUTEMAN SAMPLING GEOMETRY

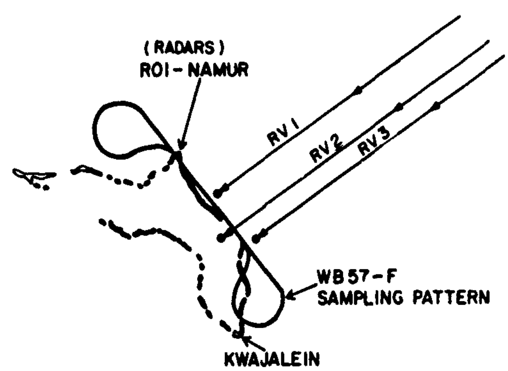

Figure 12. Flight Pattern for WB-57F Cloud Sampling. Photo-mapping pass is along the re-entry trajectories. Post-mission weather sampling in conjunction with ALCOR is along a radial from Roi-Namur toward Gellinam

After re-entry the aircraft began a series of sampling runs at 0316Z between Roi-Namur and Gellinam, with vector control from the MPS-36 tracking radar at Kwajalein and in conjunction with weather scans by ALCOR (see Section 5). Figure 13 compares the nominal altitudes and flight paths with those recorded by the MPS-36. The accuracy and constancy of the aircraft altitude was adequate

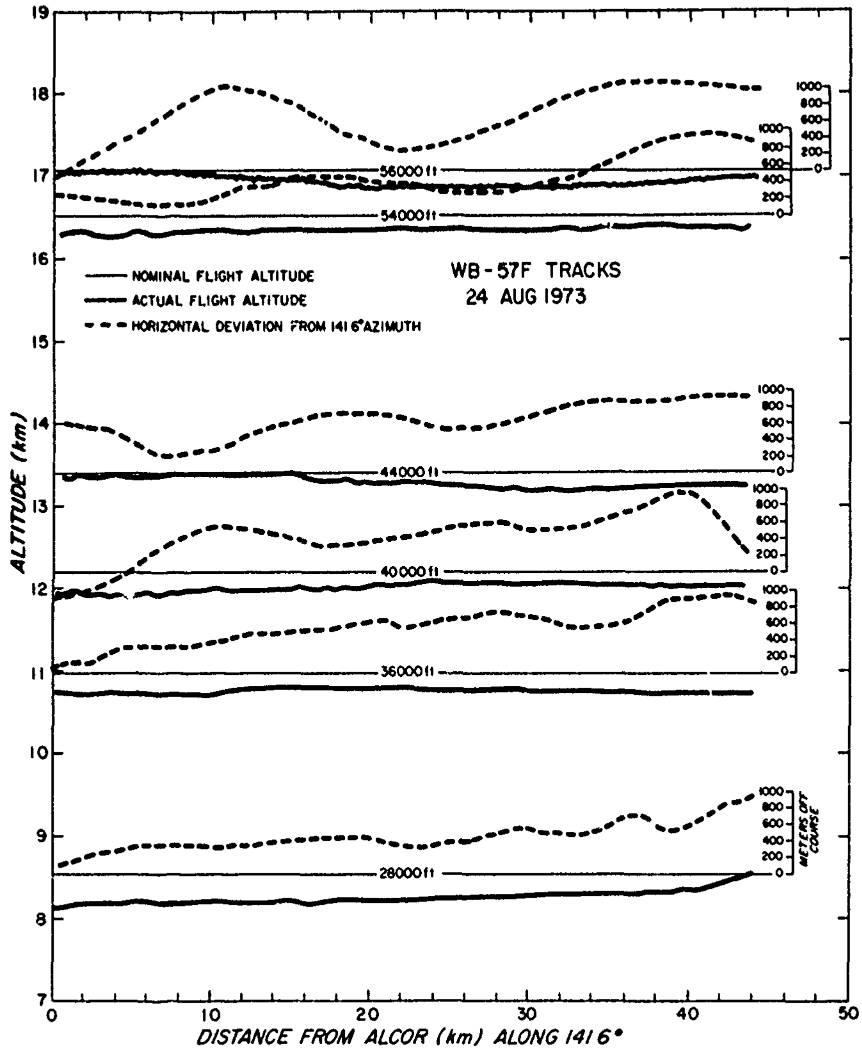

Figure 13. Deviations of the WB-57F Aircraft From Nominal Flight Paths. MPS-36 tracking data show that the aircraft is almost uniformly low by 200 m relative to the nominal altitudes. Consistent apparent deviation to the east of the sampling path is due to angular difference between ALCOR azimuth toward Gellinam and course marked on MPS-36 plot board

for the requirements of the weather data analysis. The consistent horizontal deviation appears to be due to a slight difference between the ALCOR azimuth toward Gellinam and the course marked on the MPS-36 plotting board. This deviation did not present a major problem for the data analysis, as the radar data were generally useful only to a range of about 30 km.

The first two passes encountered no visible clouds, and particle counts were recorded only on the smallest channels of the scattering probe. On the third pass at 13.3 km the aircraft was about 1 km below a very thin cloud layer which had not been visible from above, but again only a few small particles were recorded. Convective build-ups could be seen to the south and west of the re-entry corridor, but no high clouds to the east or northeast for several tens of kilometers. The fourth pass at 12.0 km came close to the cirrus which was moving in from the west, estimated by the aircrew to be a few thousand ft thick, but again recorded few particle counts. The highest water content values were observed on the fifth pass at 10.8 km, with $M = 0.001$ gm m^{-3} and $Z = 1.4 \times 10^{-3}$ $mm^6 m^{-3}$ (-28.5 dBZ) computed from the particle size data. The crew reported that most of the cirrus was above them and to the west of the flight track. A few particles were detected on the lowest pass. The film from the forward-looking camera showed that the cirrus above 10 km was moving across the flight path from the west or southwest into the re-entry corridor during the time of the correlation flights, about 1 to 2 hr after RV impact.

5. ALCOR WEATHER OBSERVATIONS FOR PVM-3

Weather data were recorded by ALCOR in support of PVM-3 in a manner similar to the PVM-4 operation. In addition to the trajectory weather scans near the time of re-entry, weather data were recorded in conjunction with the aircraft sampling flights described in Section 4. The complete ALCOR weather support is summarized in Table 4. These data were the first radar weather data supplied to AFCRL by Lincoln Laboratory, and were handled as shown in Figure 14 (PVM-4 data were supplied at a later date). Lincoln Laboratory provided AFCRL with tabulated weather reflectivity values computed from the radar cross-section values averaged over a specified number of gates within the 2.5-km data window and over a specified number of pulses. Generally the averages were computed for 11 or 21 gates, giving 160 or 310 m beamwise resolution, and 10 or 20 pulses, giving about 50 to 60 or 100 to 120 m vertical resolution on the trajectory scans. The reflectivity values were hand-plotted into a range-height array for subsequent analysis. While this procedure was more tedious than the computer processing technique subsequently used for the PVM-4 data, the numerical accuracy was

adequate both for defining the spatial structure of weather features and for obtaining reflectivity values within the cells or layers.

Table 4. ALCOR Weather Support for PVM-3 (24 August 1973)

Re-entry and Post-Impact Scans		Correlation with WB-57F Aircraft	
Time (GMT)	Trajectory	Time (GMT)	Altitude (km)
0154:24 to 0154:45	RV 1	0316:18 to 0316:51	17.0
		0318:26 to 0319:00	17.0
0205:01 to 0205:22	RV 1		
0205:43 to 0206:05	RV 2	0329:56 to 0330:30	16.4
0206:26 to 0206:43	RV 3	0332:01 to 0332:35	16.4
0207:12 to 0207:39	Vertical		
		0344:11 to 0344:47	13.4
0208:31 to 0208:52	RV 1	0346:11 to 0346:47	13.4
0209:13 to 0209:35	RV 2		
0209:56 to 0210:13	RV 3	0358:22 to 0359:00	12.2
0210:42 to 0211:09	Vertical	0400:21 to 0400:59	12.2
0211:51 to 0212:12	RV 1	0411:41 to 0412:20	10.9
0212:33 to 0212:56	RV 2	0413:45 to 0414:24	10.9
0213:16 to 0213:33	RV 3		
0214:02 to 0214:29	Vertical	0425:30 to 0426:12	8.5
		0427:30 to 0428:12	8.5

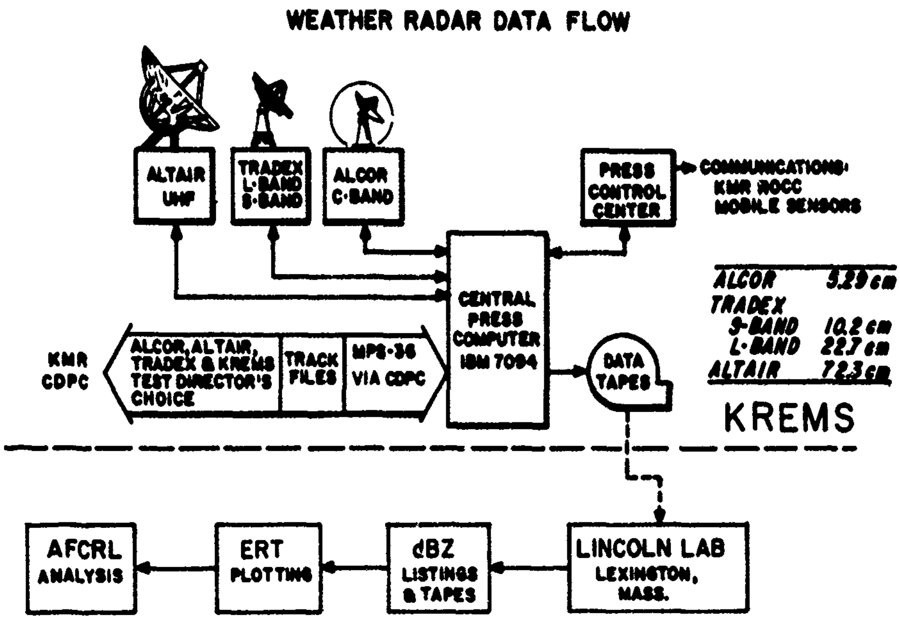

Figure 14. Radar Weather Data Flow Diagram. ALCOR is the principal weather sensor, with TRADEX S-band as backup. Hand plotting or computer processing of data provided by Lincoln Laboratory is accomplished by Environmental Research and Technology, Inc., on contract to AFCRL

Weather scans between 20 km and 1.2 km before and after the re-entries detected no echoes above the radar system noise level on any of the trajectories above 1.8 km. Echo tops near 1.8 km on the RV 1 and RV 3 post-impact scans were probably due to small low-level cumulus clouds. Peak water content of these echoes would be less than 0.001 gm m^{-3} at altitudes less than 1.5 km. Because of the lack of significant weather echoes, no figures analogous to Figure 5 are presented here. An estimate of the minimum detectable water content along the trajectories is given in Figure 15 to provide a quantitative meaning to the absence of echoes. Thus if any clouds were present at this time their water content would have been less than 0.005 gm m^{-3} at most of the altitudes of interest. Vertical scans over the radar were made for the purpose of obtaining information on any weak or high-altitude cloud layers. Because the minimum detectable reflectivity varies

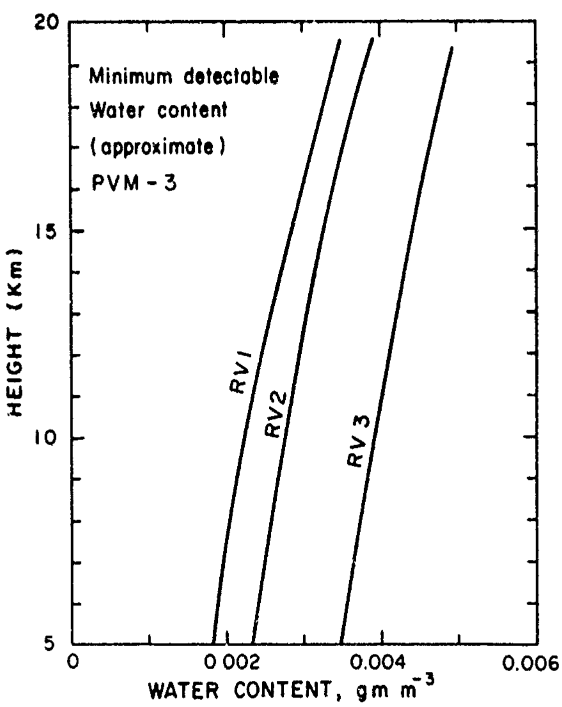

Figure 15. Approximate Minimum Detectable Ice Water Content on PVM-3 Trajectories. Any high clouds which might be present must be less dense than these values

as the square of the slant range from the radar, echo layers too weak to be detected along the trajectories, where the slant range is 20 to 60 km may be detected directly overhead. These data were averaged over two gates and 50 or more pulses to provide vertical resolution about 30 m with signal fluctuation less than 2 dB. Figure 16 shows the results of this analysis, with several echo layers all

of which are below the minimum detectable signal level on the trajectories. These signal levels correspond to water content of 0.002 gm m^{-3} or less. We believe that the echo at 7.0 km is due to fluctuations of the clear-air index of refraction associated with the sharp humidity lapse and wind shear at this altitude.

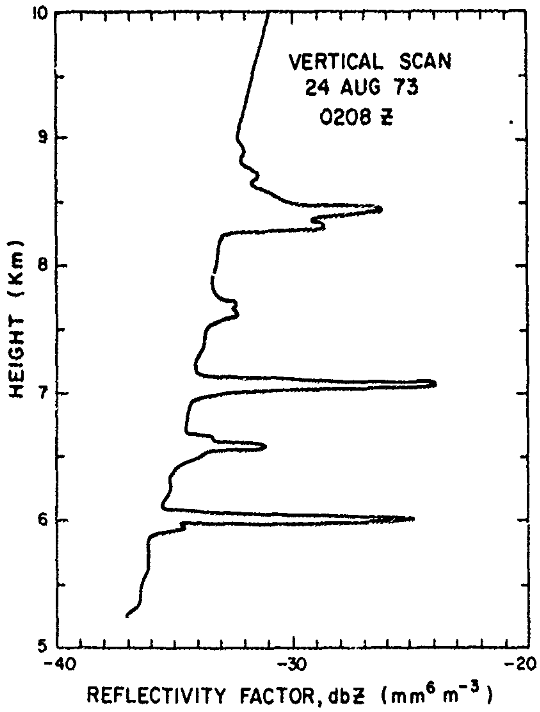

Figure 16. Reflectivity Profile Observed on ALCOR Vertical Scan Following PVM-3. Layer at 7 km is probably due to clear-air echo from layer of strong gradient of refractive index. Reflectivity of -25 dbZ represents ice water content of 0.002 gm m^{-3}

Following the post-mission radar calibrations, ALCOR made weather observations in conjunction with the WB-57F aircraft at the altitudes shown in Table 4. As the aircraft entered the flight path for each sampling pass, ALCOR commenced a scan at that altitude, starting over Gellinam and scanning toward Roi-Namur. As the aircraft reached the mid-point a second scan was begun at the same altitude over Gellinam. As the ALCOR antenna reached the zenith at the end of each scan the radar A-scope display was photographed and the heights of echo layers were determined. This information was relayed to the mission Weather Team at Range Operations to aid in directing the aircraft into clouds on succeeding passes. Examples of the A-scope display are shown in Figure 17.

The purpose of the joint operation was to provide near-simultaneous measurements of ice water content by aircraft and reflectivity by radar. These data were to be correlated to yield "Z-M" equations for interpreting the reflectivity data

recorded on the trajectories close to the time of re-entry. In practice, due to the dynamic nature of the tropical weather, it was not possible to complete the correlation analysis as originally planned. This problem was subsequently resolved by recording the radar data in a link-offset mode[7] whereby the radar data are recorded at a constant distance ahead of the aircraft.

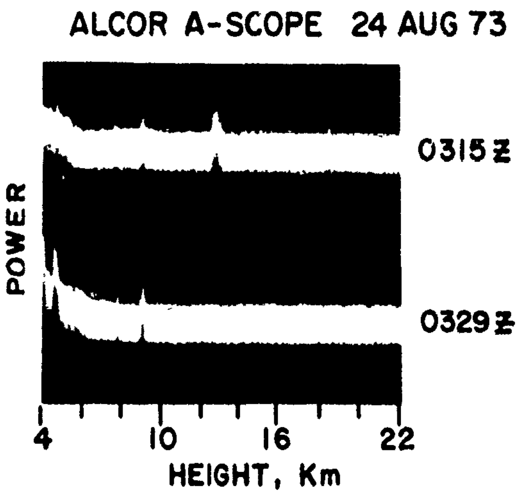

Figure 17. ALCOR A-scope Display During Post-mission Aircraft Cloud Sampling Operations. Photographs taken at the end of the first scan during the first and second aircraft passes, at 0315Z (upper) and 0329Z. Echo near 12 km is detected only during first pass. Echo near 8.5 km persists throughout the sampling period

No weather echoes were detected at the three uppermost sampling altitudes. Echoes were detected at 5 to 11 km range below 12 km altitude during the fourth pass, and a weak echo (4 to 7 dB above noise) at 12.6 to 13.1 km altitude, but none at the altitude of the aircraft. The most significant weather was observed during the fifth pass. The radar scans at this altitude are shown in Figures 18 and 19. Cirrus blowing northeastward from the convective cell west of the lagoon, described in Section 4, was mostly above the aircraft altitude, although the aircraft was in or near a cloud layer at 10.6 to 11.4 km altitude extending to about 28 km range with peak reflectivity -8 dBZ (0.16 $mm^6 m^{-3}$). The absence of such large values from the aircraft data indicates that the aircraft did not penetrate the densest parts of this layer. Typical reflectivity through much of the layer was -25 to -20 dBZ, which is closer to the values derived from the aircraft data. Temporal changes of the echo structure made it impossible to correlate the aircraft and radar data except for an approximate matching of the large-scale features. Weak echoes were detected near 9 km on the sixth aircraft pass, but only within a few kilometers of Roi-Namur.

7. Barnes, A.A., Jr., Nelson, L.D., and Metcalf, J.I. (1974) Weather documentation at Kwajalein Missile Range, 6th Conf., Aerosp. and Aeronaut. Meteor., Amer. Meteor. Soc., pp 66-69; AFCRL-TR-74-0430, Air Force Cambridge Research Laboratories, Hanscom AFB, Mass.

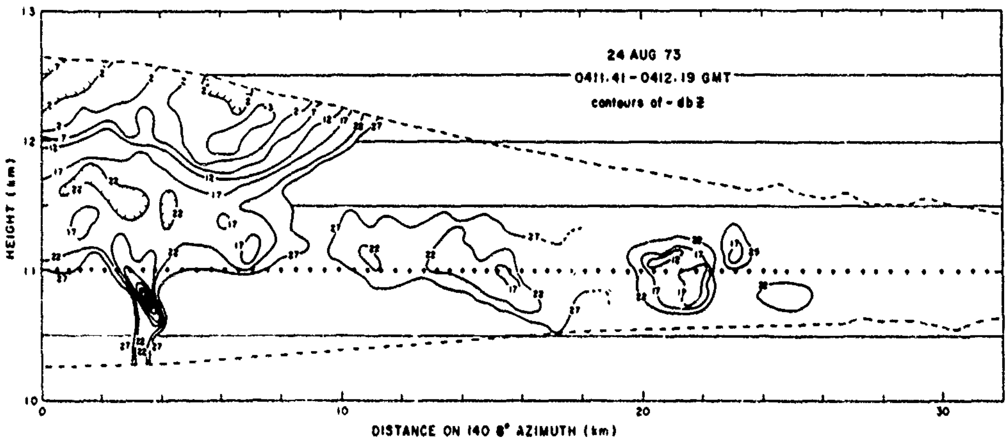

Figure 18. ALCOR Weather Scan at 0412Z, 24 August 1973, at 10.9 km. Contours are of -10 log Z, with Z in $mm^6\ m^{-3}$. Nominal flight altitude is shown by dotted line. Shape of data array is due to the orientation of the 2.5-km beamwise data window. Strongest weather echo (10 log Z = +5 at 12 km altitude and 6 km range) is above the flight altitude, but an echo layer is present at 10.6 to 11.4 km with maximum reflectivity about -8 dBZ at 21.6 km range. Intense echo at 10.8 km altitude and 3.5 km range is from the aircraft passing through the radar beam

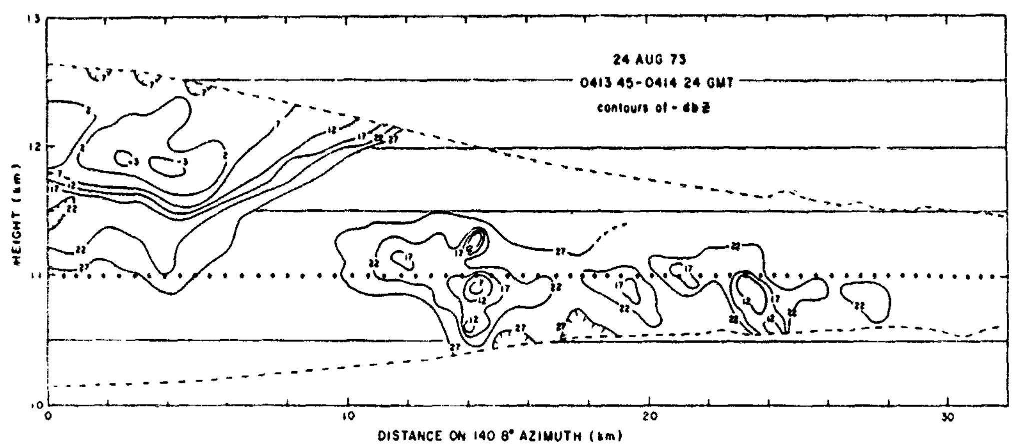

Figure 19. ALCOR Weather Scan at 0414Z, 24 August 1973, at 10.9 km. Format is identical to that of Figure 18. Strong weather echo is at lower altitude, and features of the 11-km echo layer have changed. Changes are principally due to advection of clouds by wind, which is nearly perpendicular to the orientation of the radar scan. Echo from aircraft is at 10.9 km altitude and 14 km range

6. PVM-3 SUMMARY AND CONCLUSIONS

The re-entry corridor weather satisfied the requirements for the PVM-3 mission. Low-level fair-weather cumulus with less than one-tenth coverage dotted the area. Some thin high-level clouds were visible to the north during the WB-57F photo pass, but none were present in the corridor. The lidar detected no clouds above 3 km, and ALCOR detected none above 1.8 km on the trajectories at the time of re-entry. The WSI based on measured clouds, including those detected on the radar vertical scan, was about 0.01.

Cirrus began to move into the re-entry area about 1 to 2 hr after the re-entry, at the time the WB-57F was making sampling passes. The aircraft made six passes in a descending pattern in conjunction with ALCOR weather scans. During the first four passes and the sixth pass particle counts were recorded only on the smallest size channels of the scattering probe. On the fifth pass, at 10.8 km, the aircraft encountered the highest water content, with $M = 0.001$ gm m^{-3} and $Z = 0.0014$ mm^6 m^{-3} (-28.5 dBZ) computed from the particle size data. ALCOR observed weather echoes just below the flight altitude on Pass 4, and at the flight altitude on Pass 5, with peak reflectivity about -8 dBZ.

The advection of the clouds across the flight path produced rapid temporal changes in the reflectivity structure. Because the radar and aircraft measurements were separated by as much as 5 min and 29 km it was not possible to complete the correlation analysis of the aircraft and radar data. This problem was not critical for the PVM-3 weather documentation, as very few weather echoes were detected on the trajectories by radar.

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6. Heymsfield, A.J. (1973) The Cirrus Uncinus Generating Cell and the Evolution of Cirriform Clouds, PhD Thesis, The University of Chicago.
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Symbols

AFCRL	Air Force Cambridge Research Laboratories
ALCOR	ARPA-Lincoln C-band Observables Radar
ARPA	Advanced Research Projects Agency
CDPC	Central Data Processing Computer
DAPP	Data Acquisition and Processing Program
DMSP	Defense Meteorological Satellite Program
EG&G	Edgerton, Germeshausen, and Grier, Inc.
ERT	Environmental Research and Technology, Inc.
KMR	Kwajalein Missile Range
KREMS	Kiernan Re-Entry Measurements Site
LIDAR	Light Detection and Ranging (optical analog of RADAR)
M	Water Content (liquid or ice), gm m^{-3}
MRI	Meteorology Research, Inc.
NWS	National Weather Service
PMS	Particle Measuring Systems, Inc.
PRESS	Pacific Range Electromagnetic Signature Studies
PVM	Production Verification Missile
RADOT	Range Automatic Digital Optical Tracker
ROCC	Range Operations Control Center
RV	Re-entry Vehicle
SAMSO	Space and Missile Systems Organization
SAMTEC	Space and Missile Test Center
SRI	Stanford Research Institute

TTR	Target Tracking Radar
WSI	Weather Severity Index
Z	Greenwich Mean Time
Z	Radar Reflectivity Factor, $mm^6\ m^{-3}$